

Frascati Physics Series Vol. XLVI (2007), pp. 000-000
 HADRON07: XII INT. CONF. ON HADRON SPECTROSCOPY – Frascati, October 8-13, 2007
 Plenary/Parallel Session *pick one*

OPEN FLAVOR CHARMED MESONS

P. C. Vinodkumar,

**Department of Physics, Sardar Patel University,
 Vallabh Vidyanagar-388 120, Gujarat, India.*

Ajay Kumar Rai,

*Department of Applied Sciences and Humanities,
 SVNIT, Surat-395 007, Gujarat, India.*

*Bhavin Patel,

Jignesh Pandya,

*Department of Physics, Veer Narmad South Gujarat University,
 Surat-395 007, Gujarat, India.*

Abstract

We present here recent results on the investigations of the mass spectrum (S-states and P-states), decay constants, decay widths and life time of the D, D_s , and B_c mesons within the framework of phenomenological potential models. We also present the binding energy and the masses of the di-meson molecular systems with one or more charm meson combinations. Many of the newly found experimental open charm states are identified with the orbital excitations of the conventional open charm mesons while others like X(3872), Y(3930), $D_{sJ}(2632, 2700)$ etc., are identified as molecular like states.

1 Introduction

The study of spectroscopy and the decay properties of the heavy flavour mesonic states provides us useful information about the dynamics of quarks and gluons at the hadronic scale. The remarkable progress at the experimental side, with various high energy machines such as LHC, B-factories, Tevatron, ARGUS collaborations, CLEO etc for the study of hadrons has opened up new challenges in the theoretical understanding of heavy flavour hadrons. In order to understand the structure of the newly observed zoo of open flavour meson resonances ^{1, 2, 3, 4)} in the energy range of 2-5 *GeV*, it is necessary to analyze their spectroscopic properties and decay modes based on theoretical models. Many of these states could be the excited charmed mesonic states while for many other states the possibility of multi-quark or molecular like structures are being proposed. Thus, the main objective of the present talk includes the study of spectroscopy and the decay properties of the open flavour charm mesons. We study these open charm states as the excited states of the conventional quark-antiquark systems within the frame work of a potential model ^{5, 6)}.

We also study, following the molecular interpretation of some of the recently observed meson states, the binding energy and the ground state masses of di-hadronic molecules ^{7, 8)}. For the binding energy of the di-hadronic state, we consider a large r ($r \rightarrow \infty$) limit of the confined gluon propagator employed in our earlier study on N-N integrations. ⁹⁾

2 Theoretical methodology: A Potential Scheme

For the light-heavy flavour bound system of $q\bar{Q}$ or $\bar{q}Q$ we treat the heavy-quark ($Q=c, b$) non-relativistically and the light-quark ($q = u, d, s$) relativistically within the mesonic system. The Hamiltonian for the case be written as ⁶⁾

$$H = M + \frac{p^2}{2m} + \sqrt{p^2 + m^2} + V(r) + V_{S_{\bar{Q}} \cdot S_q}(r) + V_{L \cdot S}(r) \quad (1)$$

Where M is the heavy quark mass, m is the light quark mass, p is the relative momentum of each quark, $V(r)$ is the confined part of the quark- antiquark potential, $V_{S_{\bar{Q}} \cdot S_q}(r)$ and $V_{L \cdot S}(r)$ are the spin-spin and spin orbital part of the interaction. Here we consider

$$V(r) = \frac{-\alpha_c}{r} + Ar^\nu \quad (2)$$

where $\alpha_c = \frac{4}{3}\alpha_s$, α_s being the strong running coupling constant, A and ν are the potential parameters. For computing the hyperfine and spin-orbit splitting, we consider the spin dependent part of the usual OGEP given by ¹⁰⁾

$$V_{S_{\bar{Q}} \cdot S_q}(r) = \frac{2}{3} \frac{\alpha_c}{M_{\bar{Q}} m_q} \vec{S}_{\bar{Q}} \cdot \vec{S}_q 4\pi\delta(\vec{r}), \quad V_{L \cdot S}(r) = \frac{\alpha_c}{M_{\bar{Q}} m_q} \frac{\vec{L} \cdot \vec{S}}{r^3} \quad (3)$$

We employ the harmonic oscillator wave function and use the virial theorem, to get the energy expression from the hamiltonian defined by Eqn.(1). Here μ is the wave function parameter determined using the variational method. The parameters used here are $m_{u/d} = 0.360 \text{ GeV}$, $m_s = 0.5 \text{ GeV}$, $m_c = 1.41 \text{ GeV}$, $m_b = 4.88 \text{ GeV}$, $\alpha_c = 0.48$ (for open charm meson) and $\alpha_c = 0.36$ (for open beauty-charm meson). The computed S and P wave mass spectrum of D , D_s and B_c mesons are tabulated in Table 1 alongwith the experimental and other theoretical results.

3 The decay constants and Lifetime of the open charm mesons

The decay constant of the mesons is an important parameter in the determination of the leptonic, non-leptonic weak decay processes. It is related to the wave function at the origin through Van-Royen-Weisskoff formula. Incorporating a first order QCD correction factor, we compute them using the relation ¹¹⁾

$$f_P^2 = \frac{12 |\Psi_P(0)|^2}{M_P} C^2(\alpha_s), \text{ where } C^2(\alpha_s) = 1 - \frac{\alpha_s}{\pi} \left[2 - \frac{M_Q - m_q}{M_Q + m_q} \ln \frac{M_Q}{m_q} \right] \quad (4)$$

where M_P is the ground state mass of the pseudoscalar states.

In the spectator approximation ^{6, 12)} the inclusive widths of b and c quarks decay are given by

$$\Gamma(b \rightarrow X) = \frac{9 G_F^2 |V_{Q\bar{Q}}|^2 m_b^5}{192\pi^3}, \quad \Gamma(c \rightarrow X) = \frac{5 G_F^2 |V_{Q\bar{q}}|^2 m_c^5}{192\pi^3} \quad (5)$$

and width of the annihilation channel is computed using the expression given by ^{6, 12)}

$$\Gamma(Ann i) = \frac{G_F^2}{8\pi} |V_{Q\bar{q}}|^2 f_P^2 M_P \sum_i m_i^2 \left(1 - \frac{m_i^2}{M_P^2} \right)^2 C_i \quad (6)$$

Table 1: *S-Wave and P-Wave Masses (in MeV)*

	ν	1^1S_0	1^3S_1	1^3P_0	1^3P_1	1^1P_1	1^3P_2	2^1S_0	2^3S_1
D	0.5	1922	1992	2195	2203	2210	2218	2286	2294
	1.0	1912	1993	2347	2367	2390	2414	2580	2639
	1.5	1905	2003	2388	2435	2481	2527	2599	2709
	Expt.	1864	2006	—	—	—	—	—	—
	Ebert	1875	2009	2414	2438	2459	2501	2579	2629
	Pandya	1815	1909	2385	2417	2449	2481	2653	2690
D_s	0.5	2042	2089	2353	2364	2375	2386	2466	2476
	1.0	2003	2104	2512	2544	2576	2608	2813	2847
	1.5	1937	2135	2607	2678	2750	2821	3149	3228
	Expt.	1969	2112	—	—	2535	2574	—	—
	Ebert	1981	2111	2508	2515	2560	2569	2670	2716
	Pandya	2009	2110	2385	2417	2449	2481	2778	2280
B_c	1.0	6349	6373	6715	6726	6738	6749	6821	6855
	Lattice	6280	6321	6727	6743	6765	6783	6960	6990
	ALV	6356	6397	6673	—	—	6751	6888	6910
	EFG	6270	6332	6699	6734	6749	6762	6835	7072

Expt. ³⁾, ALV ¹²⁾, EFG ¹³⁾, Pandya ¹⁴⁾, Lattice ¹⁵⁾, Ebert ¹⁶⁾

where $C_i = 1$ for the $\tau\nu_\tau$ channel and $C_i = 3|V_{Q\bar{q}}|^2$ for $Q\bar{q}$, and m_i is the mass of the heaviest fermions. Here $|V_{Q\bar{q}}|$ and $|V_{Q\bar{Q}}|$ are the respective CKM Matrix, where numerical values are obtained from ³⁾. The total width of the $Q\bar{q}$ meson decay is the addition of partial widths *i.e.* $\Gamma(total) = \Gamma(Q \rightarrow X) + \Gamma(Anni)$. In the case of the B_c meson, both the heavy quark, b and c under go the decay and the total width is obtained as $\Gamma_{total}(B_c) = \Gamma(b \rightarrow c) + \Gamma(c \rightarrow X) + \Gamma(Anni)$. The computed pseudoscalar decay constants with and without the correction factor $C^2(\alpha_s)$, the total width and lifetime of D , D_s and B_c mesons are listed in Table 2 along with other model predictions and experimental values.

4 Di-hadrons as molecular states

The low-lying di-hadronic molecular system consisting of di-meson tetra quark states are treated here by assuming non-relativistic. Hamiltonian given by

$$H = M + \frac{P^2}{2\mu} + V(R_{12}) + V_{SD}(S_1 S_2) \quad (7)$$

Table 2: *Decay constants (f_P) and lifetime of meson.*

System	ν	f_P <i>MeV</i>	$f_P(cor.)$ <i>MeV</i>	$\Gamma(total)$ $10^{-4}eV$	τ <i>ps</i>
D	0.5	231	157	6.126	1.074
	1.0	250	170	6.142	1.072
	1.5	276	187	6.167	1.067
	Expt.	—	—	—	1.040 ± 0.007
	Penin	—	195 ± 20	—	—
	Ebert	—	243 ± 25	—	—
D_s	0.5	218	156	9.148	0.719
	1.0	321	229	12.630	0.521
	1.5	451	322	18.515	0.356
	Expt.	—	—	—	0.500 ± 0.007
	Heister	—	285	—	—
	1.0	—	556	13.86	0.47
B_c	Expt.	—	—	—	$0.46^{+0.18}_{-0.16}$

Expt. ³⁾, Ebert ¹³⁾, Penin ¹⁷⁾, Heister ¹⁸⁾

where $M = m_{h_1} + m_{h_2}$, m_{h_1} and m_{h_2} are masses of the hadrons, μ is the reduced mass, P is the relative momentum of the two hadrons and $V(R_{12})$ is the residual (molecular) interaction potential between the two hadrons given by the asymptotic expression ($r \rightarrow \infty$) of the confined one gluon exchange interaction (COGEP) given by ⁹⁾

$$V(R_{12}) = \frac{-k_{mol}}{R_{12}} e^{-C^2 R_{12}^2/2} \quad (8)$$

where k_{mol} is the residual strength of the strong interaction coupling and C is the effective colour screening parameter of the confined gluons. Using a trial wave function given by

$$\psi(R_{12}) = \left(4 \frac{\Omega^{3/2}}{\sqrt{\pi}}\right)^{1/2} e^{-\Omega R_{12}^2/2} \quad (9)$$

By minimizing the expectation value of H , the ground state molecule energy is obtained as

$$E(\Omega) = M + \frac{3\Omega}{4\mu} - \frac{4k_{mol}\Omega^{3/2}}{c^2 + 2\Omega} + \frac{8}{9} \frac{\alpha_s}{m_{h_1}m_{h_2}} \vec{S}_1 \cdot \vec{S}_2 |\psi(0)|^2 \quad (10)$$

Table 3: *Low-lying masses of Multiquarks as di-hadronic molecule*

Systems $h_1 - h_2$	J^{PC}	Ω GeV^2	ψ $GeV^{3/2}$	BE GeV	Mass GeV	Expt ³⁾ GeV	Others GeV
$\pi-D$	0^{++}	0.0186	0.0757	0.022	2.027	—	—
$\pi-D^*$	1^{+-}	0.0188	0.0762	0.022	2.169	—	—
$K-D$	0^{++}	0.1415	0.3465	0.015	2.344	$D_{sJ}(2.317)$	—
$K-D^*$	1^{+-}	0.1455	0.3539	0.016	2.485	$D_{sJ}(2.460)$	—
$\rho-D$	1^{+-}	0.2684	0.5602	0.033	2.603	—	—
K^*-D	1^{+-}	0.3265	0.6489	0.039	2.718	$D_{sJ}(2.700)$	—
$\rho-D^*$	0^{++}	0.2795	0.5775	0.235	2.543	—	—
	1^{++}	—	—	0.134	2.644	—	—
	2^{++}	—	—	0.064	2.845	—	—
K^*-D^*	0^{++}	0.3420	0.6718	0.158	2.624	$D_{sJ}(2.632)$	—
	1^{++}	—	—	0.040	2.741	—	—
	2^{++}	—	—	0.077	2.976	—	—
$D-D$	0^{++}	0.3568	0.6935	0.008	3.738	—	3.723 ¹⁹⁾
$D-D^*$	1^{+-}	0.3810	0.7285	0.006	3.878	$X(3.870)$	3.876 ²⁰⁾
	0^{++}	0.4081	0.7670	0.084	3.930	—	—
D^*-D^*	1^{++}	—	—	0.040	3.974	—	—
	2^{++}	—	—	0.048	4.062	$\psi(4.040)$	3.968 ²¹⁾

Here, we have added the spin-hyperfine contribution separately. The binding energy of the di-mesons as $BE = |m_{h_1} + m_{h_2} - E|$ and the parameters $k_{mol} = 0.45$. and $c=1.25 GeV$ are employed to compute the binding energy (BE) at the charmed sector. The computed masses and binding energies of the di-meson systems are tabulated in Table 3.

5 Conclusion and Discussion:

The properties of open charm mesons *vis a vis* D , D_s and B_c are investigated by us using an effective static quark-antiquark interaction potential of the form $-\frac{\alpha_s}{r} + Ar^\nu$. We found that the potential form with $\nu = 1.0$ is consistent with the experimental results of the light-heavy flavour mesons. The relativistic treatment of light flavour and non relativistic treatment of heavy

flavour seem to be justifiable in light of the successful prediction of the various properties of light-heavy flavour mesons. In the case of B_c -meson study, the non-relativistic treatment for both the heavy quarks yields better result. The S -wave and P -wave masses, decay constants f_P , the decay widths and life time of D , D_s and B_c mesons are studied within the potential scheme with $0.5 \leq \nu < 2$. The recently observed $D_{s1}(2536)$ and $D_{sJ}^*(2857)$ are found to be the 1^3P_1 and 2^3S_1 states predicted in our model with $\nu = 1.0$. Other predicted excited states are expected to be identified and observed in future experiments.

The pseudoscalar decay constant f_P predicted without the correction terms $C^2(\alpha_s)$ of Eqn.(4) in our model with potential index $\nu = 1$ is found to be in better agreement with the experimental values of $f_{D^+} = 222.6 \pm 16 MeV$ of CLEO collaboration²²⁾ and the predicted value of $321 MeV$ for f_{D_s} is within the error bar of the experimental result of $283 \pm 17 \pm 7 \pm 14 MeV$ by BaBar collaboration¹⁾. However, the PDG average value for f_{D_s} is $267 \pm 33 MeV$ ³⁾. The ratio of $\frac{f_{D_s}}{f_D}$ in our case is 1.34 with the correction factor, while that without correction factor is 1.28 which is in accordance with the Lattice results of $1.24 \pm 0.01 \pm 0.07$ ²³⁾. The lifetime predictions of $1.07 ps$ for D and $0.52 ps$ for D_s mesons are in good agreement with the respective experimental result of $1.04 \pm 0.007 ps$ of D^\pm and $0.5 \pm 0.007 ps$ with $\nu = 1.0$.

The exotic states such as $X(3872)$, $D_{SJ}(2317, 2460, 2632, 2700 \text{ and } 2860)$, $\psi(4040)$ etc are identified as the low lying di-mesonic molecular states at the charm sector as shown in Table 3. Though there exist many attempts, the zoo of open flavour mesonic states continues to pose challenges to both experimental analysis and theoretical predictions.

Acknowledgement: Part of this work is done with a financial support from DST, Government of India, under a Major Research Project **SR/S2/HEP-20/2006**.

References

1. Aubert B et al. (BABAR Collaboration), Phys. Rev. Lett. **98**, 122011 (2007); Phys. Rev. Lett. **97** 222001 (2006).

2. D. Besson et al. (CLEO Collaboration), Phys. Rev. **D 68**, 032002 (2003).
3. W. M. Yao et al., (Particle Data Group) J. Phys. **G 33**, 1 (2006).
4. Antimo Palano, Nucl. Phys. **B 156**,105 (2006).
5. Ajay Kumar Rai, R H Parmar and P C Vinodkumar, Jnl. Phys G. **28**,2275-2280 (2002).
6. Ajay Kumar Rai and P C Vinodkumar, Pramana J. Phys. **66**(2006).
7. P Colangelo et al., Mod. Phys. Lett. **A 19**, 2083(2004).
8. Ajay Kumar Rai, Jignesh Pandya and P C Vinodkumar, Nucl. Phys. **A782**, 406-409 (2007).
9. Khadkikar S B and Vijayakumar K B , Phys. Lett. **B 254**, (1991).
10. S. S. Gershtein et al.,Phys. Rev **D51**, 3613(1995).
11. E. Braaten and S. Fleming Phys. Rev **D 52**, 181 (1995).
12. A Abd El-Hady et al., Phys. Rev **D 59**, 094001 (1999).
13. D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. **D 67**, 5663 (2003).
14. J. N. Pandya and P. C. Vinodkumar, Pramana J. Phys. **57**, 821 (2001).
15. C T H Davies et al., Phys. Lett. **B 382**, 131 (1996).
16. D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. **D 57**, 014027 (1998).
17. A. A. Penin et al., Phys. Rev. **D 65**, 054006 (2002).
18. A. Heister et al.,ALEPH Collaboration Phys.Lett.**B 528**,1(2002).
19. L. Maiani, et al., Phys. Rev. **D 71**, 014028 (2005).
20. D. Jane and M. Rosina, Few-Body Systems **35**, 175 (2004) .
21. D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Lett. **B 634**, 21 (2006).
22. Artuso M et al.,Phys. Rev. Lett.**95**, 251801 (2005).
23. Aubin C et al.,Phys. Rev. Lett.**95**, 122002 (2005).